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Development of a High-Current Plasma Lens for Focusing Broad Beams of Heavy Metal Ions

Goncharov, A.[1]; Protsenko, I.[1]; Yushkov, G.[2]; Brown, I.G.[3]
[1)] Institute of Physics, NASU, Kyiv 252650, Ukraine
[2)] High Current Electronics Institute, Tomsk 634055, Russia
[3)] Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA

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Development of a high-current plasma lens for focusing broad beams of heavy metal ions

A. Goncharov[a] and I. Protsenko
Institute of Physics, NASU, Kyiv 252650, Ukraine

G. Yushkov
High Current Electronics Institute, Tomsk 634055, Russia

I. G. Brown
Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720

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We describe the results of investigations of the manipulation of moderate energy, large area beams of heavy metal ions by a high-current electrostatic plasma lens. Electrostatic plasma lenses are essential for the focusing of high-current heavy ion beams with moderate energies of 10–100 keV. In our experiments, beams of carbon, copper, zinc, and tantalum (separately) were formed by a repetitively pulsed vacuum arc ion source with energy in the range 10–50 keV, beam current up to 0.5 A, and initial diameter 10 cm. The characteristics of the focusing of the ion beam passing through the lens were measured by a radially movable, magnetically suppressed Faraday cup. The plasma lens focusing properties were determined for a number of different distributions of the lens ring-electrode potentials. We have shown that by changing the lens electrode potential distribution we can control the lens focusing, in both the convergent and divergent regimes. Some features of heavy metal ion beam focusing under these conditions are discussed. The experiments demonstrate the versatile possibilities of the plasma lens for use with moderate-energy, high-current, heavy ion beams. [S0034-6748(00)50202-0]

I. INTRODUCTION

The current status of experimental investigation of the electrostatic plasma lens has been summarized in Refs. 1 and 2. For a high-current ion beam neutralization can be provided by electrons of sufficient density held within the beam by space charge forces. This regime occurs when the beam potential parameter I_b/v_b (where I_b is the beam current and v_b the beam ion velocity) significantly exceeds the maximum externally applied lens voltage. This quasineutral regime of the high-current plasma lens has been described in Ref. 1. Repetitively pulsed beams of hydrogen ions with current up to 2 A and energy up to 25 keV were used for entering this high-current regime. We explored the static and dynamic characteristics of the high-current plasma lens with quasineutral plasma created by fast beam ions and secondary emission electrons. Some features of the focusing of wide-aperture, low-divergence beams of hydrogen ions were investigated.[2] In these experiments good agreement was obtained with theory. It was shown that a lens without spherical aberrations can be obtained by use of an optimum magnetic field configuration and selection of the optimum distribution of externally applied ring-electrode potentials, but the maximum beam compression (ratio of focused to unfocused ion beam current density at the focal spot) was limited to disappointingly low values of 2–5. It became clear[3] that this limitation in beam compression was connected primarily to nonremovable momentum aberrations due to the azimuthal rotation of beam particles in the lens magnetic field. These aberrations depend on the ion charge-to-mass ratio and restrict the minimum radius of the beam at the focus. Beams of protons with energy 10–25 keV and low-energy, singly charged copper ions with energy 200–400 eV both came to a focus with minimum radius about 1 cm, for typical lens parameters. In our experiments with multiply charged ion beams (Cu, Zn, Mo) formed by a vacuum arc ion source[4] with energies 100–400 eV, we showed that the lens gave rise to charge-state separation of particles at the focus. For higher energy heavy ions, the effect of momentum is much reduced, and for 20–30 keV copper ions a focal spot size of 1 mm can be produced.

Some preliminary results of moderate-energy, high-current metal ion beam focusing were obtained at Kiev.[5] Using a vacuum arc ion source, we formed repetitively pulsed, wide-aperture copper ion beams with energy 10–25 keV, current up to 800 mA, pulse length about 100 ms, and initial beam diameter 5.6 cm. For optimal conditions of minimized spherical aberrations, we showed that the maximum ion current density at the beam focus is about 170 mA/cm^2—a compression of a factor of 20. These preliminary experiments carried out at Kiev provided the background for the work carried out at Berkeley, as described here.

II. EXPERIMENT

The experiments were carried out using the metal vapor vacuum arc (MEVVA)-V ion source and test stand, described in detail in Ref. 4. Low-divergence, relatively low-

[a]Electronic mail: gonchar@iop.kiev.ua

noise beams of heavy metal ions (Ta, Cu, Zn, Co, C) were formed with beam extraction voltages up to 50 keV, beam currents up to 500 mA, an initial diameter of 10 cm, and a pulse duration 250 μs. The diameter of the plasma lens input aperture was 10 cm, the length of the lens was 20 cm, and there were nine electrostatic ring electrodes. The midplane of the lens was located 34 cm from the ion source extractor. The ring electrodes were fed through a 110 kΩ voltage divider by a low-impedance, stabilized power supply. The highest potential $U_1 \leqslant +7$ kV was on the central lens electrode, and the remaining symmetrically disposed electrodes were connected in pairs to appropriate voltage divider points. The power supply provided fixed voltages to the lens electrodes during transport of the beam through the lens. The required lens magnetic field configuration was established by a number of coils surrounding the lens fed by a capacitor bank; the field was of magnitude up to 0.08 T and pulse length of 500 ms. The base pressure in the vacuum chamber was approximately 5×10^{-6} Torr. A secondary plasma was formed within the lens volume by the ion beam itself by secondary electron emission from the lens electrodes. The beam current density was measured by a radially movable, magnetically suppressed Faraday cup located 34 cm downstream from the lens midplane; the entrance aperture of the Faraday cup was 1 cm for most of the work described here, but was reduced to 3 mm diameter for some measurements so as to obtain greater radial resolution. The total current could be measured by scanning the Faraday cup radially and integrating the radial beam profile. A simplified schematic of the experimental configuration is shown in Ref. 6.

III. RESULTS

Experimental results have shown clearly, in prior work as well as here, that the plasma lens focusing characteristics depend strongly on the externally applied potential distribution along the electrostatic ring electrodes. In the work described here we carried out experiments for several different axial electrode potential distributions. The results obtained for the case of a tantalum ion beam are described in the following.

Very Short Potential Distribution. The very short potential distribution refers to the case when the central lens ring electrode, alone, has a positive potential, and all the other eight electrodes are grounded. The ion current density j_i of the tantalum ion beam at the Faraday cup location was measured as a function of central electrode voltage (''lens voltage'') U_L and of the beam accelerating voltage U_{acc}. These dependencies have a typical bell-shaped variation (Fig. 1). The compression of the ion beam at the focus increases with beam energy up to a maximum of a factor of approximately 7 for $U_{\mathrm{acc}}=22$ kV and a lens electrode voltage $U_L=6.6$ kV.

Short Potential Distribution. This distribution refers to the case when the three central lens ring electrodes have a positive potential and the other six electrodes are grounded. The ion current density j_i of the tantalum ion beam at the Faraday cup was measured as a function of voltage U_L and U_{acc}. The variations are similar to those described above, but now the maximum beam compression at the focus is greater, up to a factor of approximately 13.

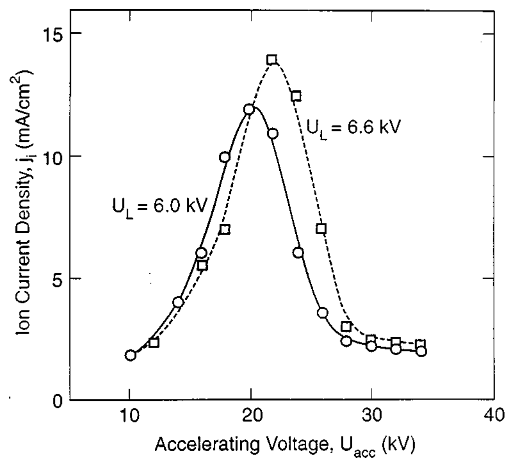

FIG. 1. Tantalum ion beam current density j_i at the Faraday cup as a function of beam accelerating voltage U_{acc}. Very short potential distribution. ($B=400$ G).

Long Potential Distribution. For the case when the five central electrodes of the lens have the same positive potential U_L and the four outermost electrodes are grounded, the focusing characteristics of the lens cease to be resonant. One can see in Figs. 2 and 3 that the beam current density increases with beam energy by up to a factor of about 5, and has no characteristic maximum in its U_L variation.

Very Long Potential Distribution. Finally, when all except the two outermost electrodes are held at a potential U_L, the focusing properties of the lens change dramatically. The lens now operates in a defocusing mode. The dependencies $j_i(U_L)$ for different values of U_{acc} are shown in Fig. 4. One can see that the lens causes a significant decrease of beam density at the collector, and the higher the beam energy the greater is this unexpected effect.

Optimal Potential Distribution. The effect of spherical aberrations of the lens volume is minimized for the case of the optimum distribution of electrode potentials. In this case $\Phi(R,z) \sim B_z(0,z)$. For this condition, the dependencies

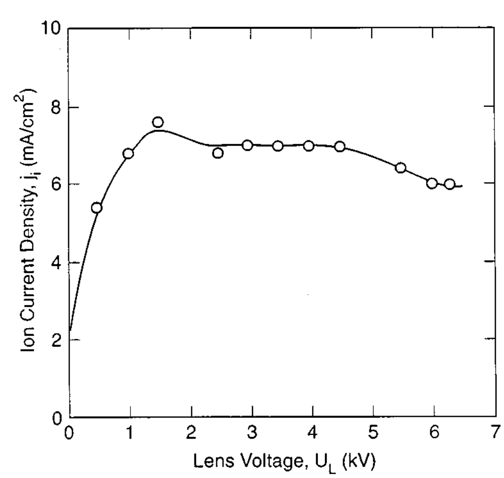

FIG. 2. Tantalum ion beam current density j_i at the Faraday cup as a function of lens central electrode voltage U_L. Long potential distribution ($B=800$ G; $U_{\mathrm{acc}}=20$ kV).

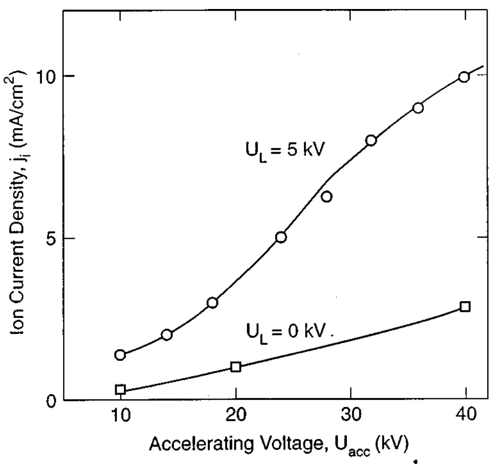

FIG. 3. Tantalum ion beam current density j_i at the Faraday cup as a function of beam accelerating voltage U_{acc} for lens-on ($U_L = 5$ kV) and lens-off as indicated. Long potential distribution ($B = 800$ G).

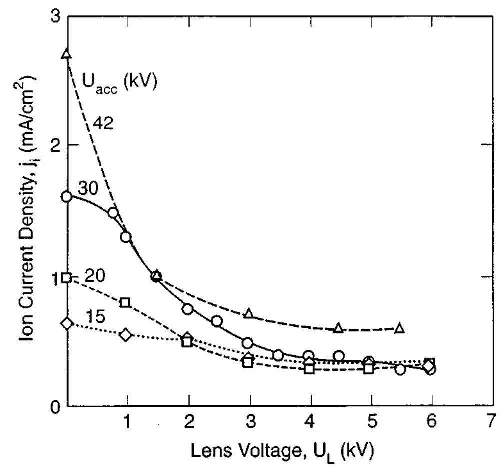

FIG. 4. Tantalum ion beam current density j_i at the Faraday cup as a function of lens central electrode voltage U_L, for different values of beam accelerating voltage U_{acc}. Very long potential distribution ($B = 600$ G).

$j_i(U_L, U_{acc})$ have a distinctive sharply peaked character, as seen in Figs. 5(a) and 5(b). The maximum beam compression at the focus is almost a factor of 25. The Faraday cup entrance aperture for these data was 1 cm; for a 3 mm aperture the measured maximum compression increased to a factor of 30. The good beam focusing could be visually observed in the form of a bright spot with an overall diameter of 2–3 cm at the Faraday cup. Note also that the time resolved pulse shape of the focused beam follows the initial beam pulse shape quite well. That is, under these conditions the lens neither distorts the focused beam pulse shape nor introduces any additional beam noise.

IV. DISCUSSION

The defocusing mode of the plasma lens accessed for the case of the very long potential distribution as described in the preceding, calls for explanation. This behavior seems to be in disagreement with the theory and also with previous experiments.[5] We explain this observation in the following way. In the present lens design, the outermost ring electrodes, which are grounded, are located further from the lens midplane than are the magnetic field coils. Consequently, the magnetic field strength at the axial location of these electrodes is about the same as for their neighboring electrodes.

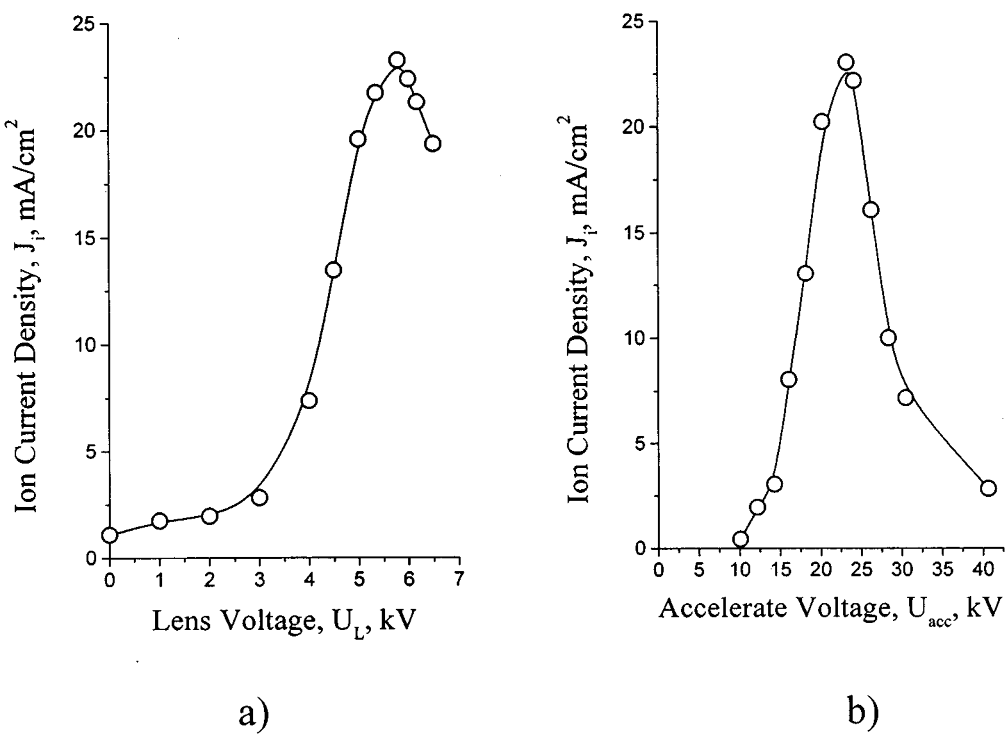

FIG. 5. (a) Tantalum ion beam current density j_i at the Faraday cup as a function of lens central electrode voltage U_L. Optimal potential distribution ($B = 800$ G; $U_{acc} = 22$ kV). (b) Tantalum ion beam current density j_i at the Faraday cup as a function of beam accelerating voltage U_{acc}. Optimal potential distribution ($B = 800$ G; $U_L = 5.5$ kV).

Thus, secondary electrons, necessary for beam space charge compensation and for the formation of equipotential surfaces within the lens volume, leave the nearest electrodes with high positive potential. The beam within the lens is less space-charge-neutralized according to its own unneutralized potential parameter I_b/v_b; (see Fig. 4, showing that as energy increases, the beam current increases faster than its velocity). The defocusing properties of the plasma lens for the very long potential distribution can be similarly explained. The defocusing regime could find application as a tool for the formation of a more homogeneous or ''soft'' profile of the ion beam at a moderately illuminated target. The plasma lens could possibly provide a tool for focusing broad multiply charged beams to higher current density since the focal length of the lens does not depend on the *Q/A* (it is a purely electrostatic optical system). Another application could be in the nonresonant regime (as in Figs. 2 and 3); this regime could provide a parallel beam at the target, having natural divergence from the ion source and to provide a normal (perpendicular) pitch angle of the ion beam at the target.

The experiments demonstrate the wide ranging possibilities of the electrostatic plasma lens operating with moderate-energy, high-current, heavy ion beams. The plasma lens may be used as a strong-focusing device for creation of a spot with high-energy and mass concentration in the focus. For the optimal lens electrode potential distribution the maximum Ta ion beam compression at the focus was a factor of 30. At its present stage of development, the electrostatic plasma lens provides a tool that could be of value for high dose ion implantation, for example. The further removal of lens spherical aberrations could lead to the ability to focus high-current beams by a compression of much greater factors than those observed here. This could open up some novel areas for the practical application of high-current ion beams.

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[1] A. Goncharov, A. Dobrovolsky, A. Zatuagan, and I. Protsenko, IEEE Trans. Plasma Sci. **21**, 573 (1993).
[2] A. Goncharov, A. Zatuagan, and I. Protsenko, IEEE Trans. Plasma Sci. **21**, 578 (1993).
[3] A. Goncharov, A. Dobrovolsky, I. Litovko, I. Protsenko, and V. Zadorodzny, IEEE Trans. Plasma Sci. **25**, 709 (1997).
[4] I. Brown, Rev. Sci. Instrum. **65**, 3061 (1994).
[5] A. Goncharov, S. Gubarev, A. Dobrovolsky, I. Protsenko, I. Litovko, and I. G. Brown, IEEE Trans. Plasma Sci. **27**, 1068 (1999).
[6] A. Goncharov, I. Protsenko, G. Yushkov, and I. Brown, Appl. Phys. Lett. **75**, 911 (1999).